SEE Test Report
Single-Event Gate Rupture Testing of the International Rectifier IRH7360SE Power nMOSFET

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I. Introduction

This study was undertaken to determine the single-event gate rupture (SEGR) susceptibility of the IRH7360SE power MOSFET. Heavy-ion testing was conducted at the Texas A&M University Cyclotron Single Event Effects Test Facility (TAMU). The test devices were protected from single-event burnout (SEB) using a current-limiting resistor at the drain node; this resistance was increased after two devices experienced apparent SEB. The failure mode for all subsequent devices was SEGR. All tests were conducted at normal beam incidence in air. With the gate-source voltage (Vgs) held at 0 V, the minimum last pass/first fail drain-source voltage (Vds) for these devices was 400V/>400V under 1012 MeV krypton irradiation, and 190V[1]/200V under 1310 MeV silver irradiation. At –15Vgs, the minimum last pass/first fail Vds was 320V/330V (SEB) with krypton and 130V/140V with silver irradiation.

II. Devices Tested

The initial sample size for the testing was 11 pieces. One piece (S/N #2) was damaged during pretest electrical characterization, leaving 10 pieces for testing. These pieces were manufactured by International Rectifier (IR) and delivered in TO-3 packaging without lids.

The IRH7360SE is a 24 amp, 400 volt n-channel vertical power MOSFET, manufactured under IR's 4th generation of radiation-hardened HEXFET® technology. In addition to total-dose hardening, this device is considered single-event effect (SEE) hardened as denoted by the SE in the vendor part number. Vendor electrical parameter specifications are given in Appendix A. The devices were visually inspected and electrically characterized on-site by Anthony Phan, MEI Technologies. The die measures approximately 0.102 cm by 0.141 cm, giving a die area of 0.014 cm^2. The overlayer thickness for LET calculation is approximated to be 10 µm silicon-equivalent; the epilayer thickness is approximated to be 40 µm based upon literature reports for 400 volt power MOSFETs.

III. Test Facility

Facility: Texas A&M University Cyclotron Single Event Effects Test Facility, 15 MeV/u tune.
Flux: 5×10^3 particles/cm^2/s.
Fluence: 5×10^5 p/cm^2, or less if destructive events occurred sooner.

Ion	Incident LET (MeV•cm^2/mg)	Energy (MeV)	Range (µm in Si)
^{84}Kr	28.1	1012	131
^{109}Ag	41.9	1310	121.4

[1] Full SEGR occurred at 210Vds or higher in all devices; however, one device experienced a 4µA microbreak at its initial 200Vds bias. The last-pass 190Vds is therefore an extrapolation of these data.

IV. Test Setup

The test circuit, as shown in Figure I, for the power MOSFET contains a Keithley 2400 source meter to provide the gate voltage (set to 0V or -15V during irradiation) while measuring the gate current. Gate current was limited to 1mA, and recorded via GPIB card to a desktop computer at 100 ms intervals. A filter was placed at the gate node of each device under test (DUT) to dampen noise at the gate. An Agilent 6035A power supply provided the appropriate Vdd; the drain and source currents were monitored by HP34401A digital multimeters placed across a 1Ω, 50W resistor and recorded via GPIB card at 100 ms intervals. A current probe at the drain node and a differential probe across the 1Ω source resistor fed into a digital oscilloscope that was set to trigger on transients of a predetermined size, saving them to file. To protect the devices from single-event burnout, an additional 500Ω or 1000Ω, 50W resistor was placed in series at the drain node, and no stiffening capacitor was used. In preparation for ion exposure, each DUT in turn was mounted on the test board (Figure II), placed 3.5 cm (krypton) or 2.6 cm (silver) from the beam aperture, and centered within the 2-inch beam diameter. Ion exposures were conducted at normal angle of incidence to the DUT.

The test setup was controlled via custom LabView codes written by Hak Kim, MEI Technologies, for this test. One program controlled the power supplies, gate current limit, oscilloscope monitoring and transient capture, and gate, drain, and source current sampling and recording. The second LabView code was designed to perform a parametric analysis of each DUT prior to irradiation, recording Igs as a function of Vgs, gate threshold voltage, drain-source breakdown voltage, and zero gate voltage drain current. In addition, the code conducted a gate stress test after each run to test the integrity of the gate dielectric and measure the gate leakage current.

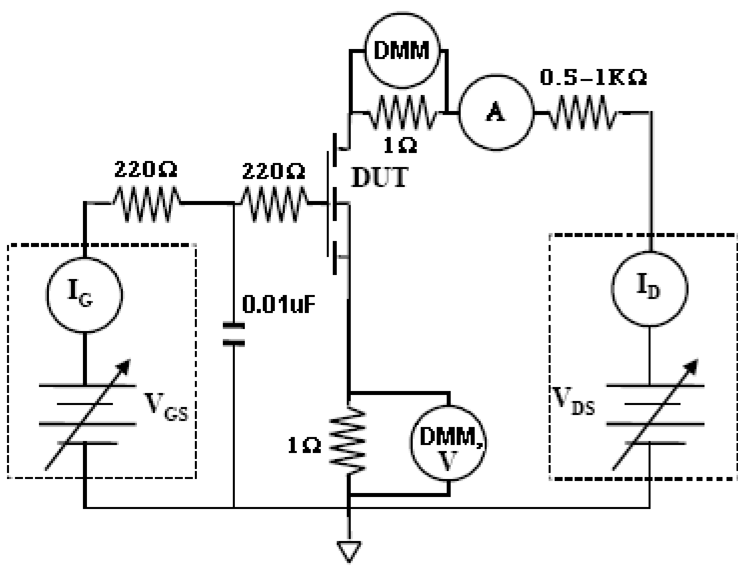

Figure I. Test setup for the IRH7360SE power MOSFET.

Table A. Test Equipment.

Node	Make/model	s/n
Gate	Keithley 2400 source meter	1175951
Drain	Agilent 6035A power supply HP34401A DMM Tektronix TDS784C oscilloscope Tektronix TCP202 current probe	5G41000135 hp3146A47434 B01226
Source	HP34401A DMM Tektronix ADA 400A differential probe	hp3146A48142

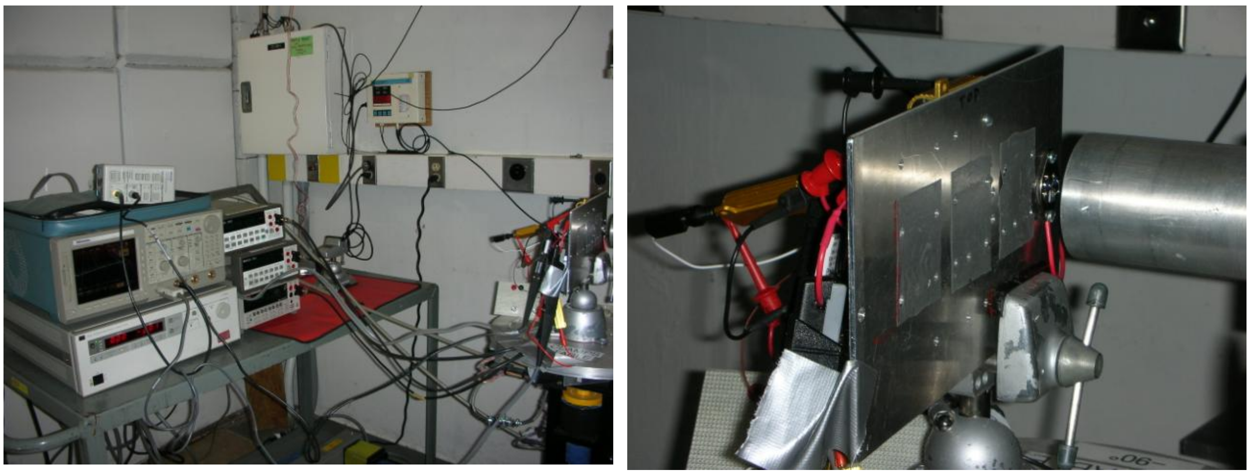

Figure II. Test equipment setup at TAMU for the IRH7360SE power MOSFET. In right photo, DUT is positioned in the beam line.

V. Test Results

Tests were performed at Texas A&M University Cyclotron Single Event Effects Test Facility on March 5-6, 2009. Two different monoenergetic ion beams (1012 MeV krypton and 1310 MeV silver) were used; all tests were conducted with the beam at normal angle of incidence to the DUT. Complete test data and conditions are provided in Appendix B. Appendix C contains a few examples of the strip tape data. Following each run, a gate stress test was performed in which the gate current was measured while the gate voltage was swept from 0V to 20V, then from 0V to -20V, at 0Vds. Devices were circuit-protected from single-event burnout (SEB) with a 500Ω resister at the drain; following two device failures by apparent SEB, this resistance was increased to 1000Ω. All subsequent device failures were due to gate rupture. The device was considered completely ruptured when the gate leakage current reached the maximum current limit of 1mA. Prior to total rupture, smaller ruptures often occurred resulting in gate leakage currents above the 100nA vendor specified maximum. It was not within the scope of this study to evaluate device reliability following such a "microbreak"; that is, no conclusions can be drawn as to whether such a break would lead to future total failure during normal operating conditions.

Figure III shows a plot of the single-event effect safe operating area (SOA) as defined by the vendor, to which the test results from this study have been added. The higher-energy ions used in this study result in no reduction of the SOA with krypton ions, but a reduction by 40% at 0Vgs and 60% at –15Vgs with silver ions, as compared with the SOA defined in the vendor data sheet using lower-energy heavy ions. Note that the LETs of the test ions closely match those used in the vendor tests. In this plot, LET was calculated for silver (krypton is not available in the calculator) using the Brookhaven National Laboratory Tandem Van de Graaff Accelerator TVDG LET calculator, as this calculator was used by the vendor. At

TAMU, LETs are determined using the SRIM code, resulting in a slightly higher value. Details of the test results are described below.

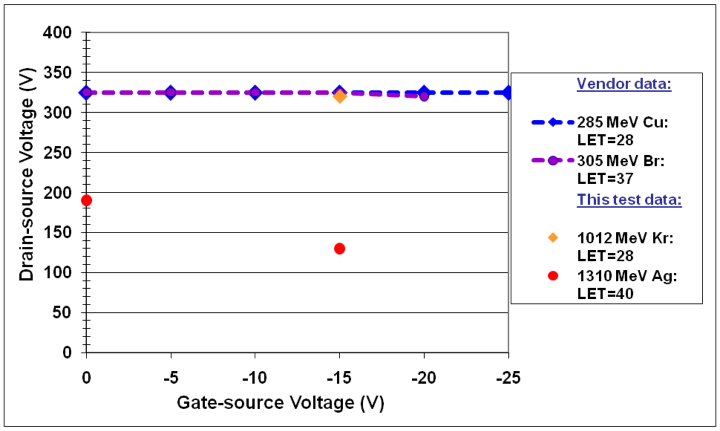

Figure III. Device single-event effect safe operating area as defined by vendor testing with low-energy heavy ions (blue/purple dotted lines) and by test results from this work with higher-energy ions (orange/red markers).

A. Krypton Ions

One DUT was tested with Vgs held at 0V, incrementing Vds by 5-10V at each beam run. This DUT (#1) did not fail at the maximum test Vds of 400V; it was electrically recharacterized and tested at -15Vgs, where it again passed at 400Vds. Two additional DUTs were then tested at -15Vgs, incrementing Vds by 10V at each beam run. The first DUT experienced apparent destructive SEB at 340Vds (Figure C1); the second DUT experienced apparent destructive SEB at 330Vds. After these runs, the drain resistor was increased to 1kΩ. As of this time, post-test SEM analysis has not been performed to confirm that SEB was the failure mechanism.

B. Silver Ions

An initial DUT was tested at 0Vgs and 250Vds; it experienced a very small increase (<100nA) in gate current about 45 seconds following the opening of the beam shutter. Repeated post-run gate stress tests resulted in the current-limited 1mA gate rupture at positive 20Vgs, but 720-770µA Igs at -20Vgs (see Figure C2A); this DUT was reexposed to the beam at 250Vds, during which time it experienced a more substantial microbreak, with full rupture occurring at both ± 20Vgs during the post-run gate stress test (see Figure C2B).

Three additional DUTs were tested at 0Vgs. DUT #9 underwent full gate rupture during beam exposure (Figure C3) at 230Vds after passing without incident at 220Vds. Examination of the captured DMM data reveals that the gate, drain, and source currents all increased within the same capture window of time; the precise failure sequence resulting in the broken gate is therefore undeterminable. The next DUT (#10) experienced a small rupture (<1µA) at the initial 200Vds tested, a larger (>1µA) rupture during irradiation with 210Vds bias, with full gate rupture during the gate stress test after this latter run. Finally, the third DUT was initially biased at 170Vds, with 10V increments at each run. At 210Vds, it experienced a very small (<100nA) rupture during irradiation but broke during the gate stress test.

Finally, two DUTs were tested at -15Vgs. The first DUT experienced a microbreak during irradiation at 140Vds, exhibiting as much as 20µA gate leakage current during the stress test (Figure C4A). This device experienced a large rupture at 160Vds, with full rupture (1 mA Igss – the current limit of the gate supply) occurring during the stress test (Figure C4B). DUT #1, having survived prior testing with krypton, was electrically recharacterized (see Table B1); it experienced a large rupture at 140Vds, with full gate rupture (1 mA Igss) occurring during the post-run gate stress test (Figure C5).

Appendix A

TABLE A1. IRH7360SE Vendor-specified Electrical Parameters (partial list).

Parameter	Condition	MIN	MAX	Units
Gate Threshold Voltage (VGSth)	Vds = Vgs, Id = 1.0 mA	2.5	4.5	V
Zero Gate Voltage Drain Current (Idss)	Vds = 320V, Vgs = 0V		50	uA
Drain-Source Breakdown Voltage (BVdss)	Vgs = 0V, Id = 1mA	400		V
Gate-Source Leakage Current	Vgs = +/- 20V, Vds = 0V		+/- 100	nA
Drain-Source On-State Resistance	Vgs = 12V, Id = 15A (pulse test)		0.20	Ohms
Source-Drain Diode Forward Voltage	Vgs = 0V, Is = 24A (pulse test)		1.4	V
Turn-on Delay Time (Td(on))	Vgs = 12V, Vdd = 200V, Id = 24A, Rg = 2.35ohms		35	ns
Rise Time (tr)	Vgs = 12V, Vdd = 200V, Id = 24A, Rg = 2.35ohms		100	ns
Turn-off Delay Time (td(off))	Vgs = 12V, Vdd = 200V, Id = 24A, Rg = 2.35ohms		120	ns
Fall Time (tf)	Vgs = 12V, Vdd = 200V, Id = 24A, Rg = 2.35ohms		100	ns

Appendix B

Table B1: Pretest Characterization of DUTs.

Part SN	Vth (Volts)	BVdss (Volts)	Idss (μA)	Igss +/- (nA)
1	4.5	pass	1.04	20/-15
3	4.4	pass	0.383	22.9/-19.5
4	4.38	pass	2.13	25.7/-20.4
5	4.37	pass	0.371	25.8/-20.5
6	4.43	pass	0.443	21.3/-17.9
7	4.36	pass	0.683	20.9/-17.8
8	4.4	pass	0.395	29.8/-21.3
9	4.44	pass	-0.108	28.6/-19.0
10	4.38	pass	0.204	24.1/-18.6
11	4.34	pass	0.635	21.9/-17.2
1 (pre Ag runs)	4.38	pass	0.635	22.9/-16.5

Table B2: Raw test data from 5-6 March 2009. Beam diameter = 2"; LET, energy, and range are after beam airgap of 3.5cm for Kr, 2.6cm for Ag.

Run	Ion	LET	Energy	Range	Ave. Flux	Fluence	Dose	Cum.	Angle	S/N	VGS	VDS	Vth	Pass/	
#		*MeV.cm2/mg*	*MeV*	*μm*	*#/cm2/sec*	*#/cm2*	*rad (Si)*	*Dose*	*deg*		*V*	*V*	*V*	Fail	comments
1	Kr	28.1	1012	131	4.50E+03	5.31E+05	2.39E+02	2.39E+02	0	1	0	270	4.5		data not saved- incorrect path name
2	Kr	28.1	1012	131	4.35E+03	4.98E+05	2.24E+02	4.63E+02	0	1	0	280	4.5		
3	Kr	28.1	1012	131	5.13E+03	4.99E+05	2.24E+02	6.87E+02	0	1	0	290			
4	Kr	28.1	1012	131	5.01E+03	5.02E+05	2.26E+02	9.13E+02	0	1	0	300			
5	Kr	28.1	1012	131	4.82E+03	5.00E+05	2.25E+02	1.14E+03	0	1	0	310	4.5		
6	Kr	28.1	1012	131	5.06E+03	4.99E+05	2.24E+02	1.36E+03	0	1	0	320			
7	Kr	28.1	1012	131	5.24E+03	5.02E+05	2.26E+02	1.59E+03	0	1	0	330			
8	Kr	28.1	1012	131	5.53E+03	5.00E+05	2.25E+02	1.81E+03	0	1	0	340			
9	Kr	28.1	1012	131	5.21E+03	4.99E+05	2.24E+02	2.04E+03	0	1	0	350			
10	Kr	28.1	1012	131	5.10E+03	5.02E+05	2.26E+02	2.26E+03	0	1	0	355			
11	Kr	28.1	1012	131	5.18E+03	5.00E+05	2.25E+02	2.49E+03	0	1	0	360			
12	Kr	28.1	1012	131	5.12E+03	4.99E+05	2.24E+02	2.71E+03	0	1	0	365			
13	Kr	28.1	1012	131	4.97E+03	4.99E+05	2.24E+02	2.94E+03	0	1	0	370	4.49		
14	Kr	28.1	1012	131	4.94E+03	5.02E+05	2.26E+02	3.16E+03	0	1	0	375			
15	Kr	28.1	1012	131	4.76E+03	5.02E+05	2.26E+02	3.39E+03	0	1	0	378			
16	Kr	28.1	1012	131	4.38E+03	5.00E+05	2.25E+02	3.61E+03	0	1	0	385			
17	Kr	28.1	1012	131	4.52E+03	5.02E+05	2.26E+02	3.84E+03	0	1	0	390	4.49		
18	Kr	28.1	1012	131	4.63E+03	5.00E+05	2.25E+02	4.06E+03	0	1	0	395			
19	Kr	28.1	1012	131	4.99E+03	5.02E+05	2.26E+02	4.29E+03	0	1	0	400	4.49	PASS	recharacterize DUT for new Vgs
20	Kr	28.1	1012	131	5.05E+03	4.99E+05	2.24E+02	4.51E+03	0	1	-15	340			
21	Kr	28.1	1012	131	5.38E+03	4.99E+05	2.24E+02	4.74E+03	0	1	-15	350			
22	Kr	28.1	1012	131	5.05E+03	5.00E+05	2.25E+02	4.96E+03	0	1	-15	360			
23	Kr	28.1	1012	131	5.07E+03	4.99E+05	2.25E+02	5.19E+03	0	1	-15	370			
24	Kr	28.1	1012	131	5.39E+03	5.02E+05	2.26E+02	5.41E+03	0	1	-15	380	4.5		
25	Kr	28.1	1012	131	5.01E+03	5.00E+05	2.25E+02	5.64E+03	0	1	-15	390			
26	Kr	28.1	1012	131	5.11E+03	5.03E+05	2.26E+02	5.86E+03	0	1	-15	400		PASS	
27	Kr	28.1	1012	131	6.00E+03	4.98E+05	2.24E+02	2.24E+02	0	5	-15	300			
28	Kr	28.1	1012	131	5.62E+03	5.02E+05	2.26E+02	4.50E+02	0	5	-15	320			
29	Kr	28.1	1012	131	5.47E+03	4.98E+05	2.24E+02	6.74E+02	0	5	-15	330	4.37		
30	Kr	28.1	1012	131	4.61E+03	3.11E+04	1.40E+01	6.87E+02	0	5	-15	340		SEB	

Run	Ion	LET	Energy	Range	Ave. Flux	Fluence	Dose	Cum.	Angle	S/N	VGS	VDS	Vth	Pass/	
#		***MeV.cm2/mg***	***MeV***	***µm***	***#/cm2/sec***	***#/cm2***	***rad (Si)***	***Dose***	***deg***		***V***	***V***	***V***	**Fail**	**comments**
31	Kr	28.1	1012	131	5.57E+03	5.03E+05	2.26E+02	2.26E+02	0	6	-15	320			
32	Kr	28.1	1012	131	5.56E+03	2.35E+05	1.06E+02	3.32E+02	0	6	-15	330	4.43	SEB	
33	Kr	28.1	1012	131	5.74E+03	5.00E+05	2.25E+02	2.25E+02	0	7	-35	0			Switch to 1k resistor at drain
34	Kr	28.1	1012	131	5.81E+03	4.98E+05	2.24E+02	4.49E+02	0	7	-45	0	4.37		
35	Kr	28.1	1012	131	5.49E+03	5.01E+05	2.25E+02	6.74E+02	0	7	-55	0			
36	Kr	28.1	1012	131	5.41E+03	5.03E+05	2.26E+02	9.00E+02	0	7	-65	0	4.36		
37	Kr	28.1	1012	131	4.91E+03	5.34E+04	2.40E+01	9.24E+02	0	7	-75	0		SEGR	
38	Ag	41.9	1310	121.4	5.52E+03	4.98E+05	3.34E+02	3.34E+02	0	8	0	250	4.39	SEGR	1mA/-0.8mA on sweep
39	Ag	41.9	1310	121.4	5.56E+03	1.61E+05	1.08E+02	4.42E+02	0	8	0	250	4.39	SEGR	now 1mA/-1mA
40	Ag	41.9	1310	121.4	5.60E+03	5.00E+05	3.36E+02	3.36E+02	0	9	0	220			
41	Ag	41.9	1310	121.4	5.55E+03	4.99E+05	3.35E+02	6.71E+02	0	9	0	230		SEGR	during run
42	Ag	41.9	1310	121.4	5.58E+03	4.97E+05	3.34E+02	3.34E+02	0	10	0	200			microbreak
43	Ag	41.9	1310	121.4	5.81E+03	5.00E+05	3.36E+02	6.70E+02	0	10	0	210		SEGR	broke on sweep
44	Ag	41.9	1310	121.4	5.56E+03	5.01E+05	3.37E+02	3.37E+02	0	3	0	170			
45	Ag	41.9	1310	121.4	5.76E+03	4.98E+05	3.34E+02	6.71E+02	0	3	0	180			
46	Ag	41.9	1310	121.4	5.47E+03	4.99E+05	3.35E+02	1.01E+03	0	3	0	190			
47	Ag	41.9	1310	121.4	5.47E+03	4.98E+05	3.35E+02	1.34E+03	0	3	0	200			
48	Ag	41.9	1310	121.4	5.42E+03	5.01E+05	3.37E+02	1.68E+03	0	3	0	210		SEGR	broke on sweep
49	Ag	41.9	1310	121.4	5.03E+03	5.01E+05	3.37E+02	3.37E+02	0	11	-15	120			
50	Ag	41.9	1310	121.4	4.80E+03	5.00E+05	3.36E+02	6.73E+02	0	11	-15	130			
51	Ag	41.9	1310	121.4	5.06E+03	5.02E+05	3.37E+02	1.01E+03	0	11	-15	140			microbreak
52	Ag	41.9	1310	121.4	5.06E+03	5.01E+05	3.36E+02	1.35E+03	0	11	-15	150			
53	Ag	41.9	1310	121.4	4.98E+03	1.44E+05	9.70E+01	1.44E+03	0	11	-15	160		SEGR	during run
54	Ag	41.9	1310	121.4	4.69E+03	5.01E+05	3.36E+02	3.36E+02	0	1	-15	120			(recharacterized pre-run)
55	Ag	41.9	1310	121.4	4.79E+03	5.00E+05	3.36E+02	6.72E+02	0	1	-15	130			
56	Ag	41.9	1310	121.4	4.76E+03	3.60E+05	2.42E+02	9.14E+02	0	1	-15	140		SEGR	during run

Appendix C

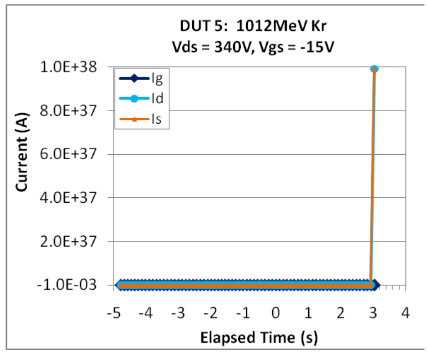

Figure C1. Gate, drain, and source currents during irradiation with krypton. This DUT experienced apparent destructive SEB three seconds following the opening of the beam shutter.

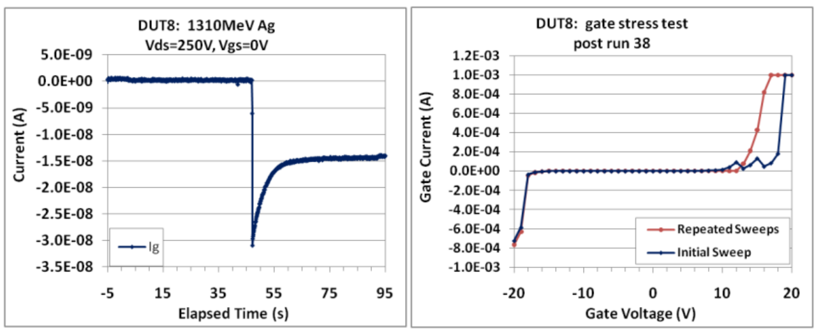

Figure C2A. Gate current during irradiation showing a very small increase after 45 seconds of exposure (left), and gate current during post-run gate stress test (right) showing minimal change upon repeated sweeps. The 1mA current limit is reached only under positive gate voltage stress.

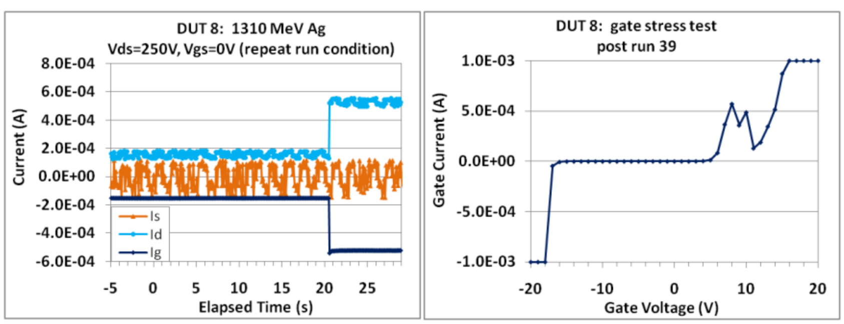

Figure C2B. Repeat of bias conditions in C2A. Gate, source, and drain currents during irradiation, and gate current during post-run gate stress test. The DUT experiences a more substantial microbreak during irradiation, with full gate rupture during the post-run stress test where Igs is now at the 1mA limit at both ±20Vgs.

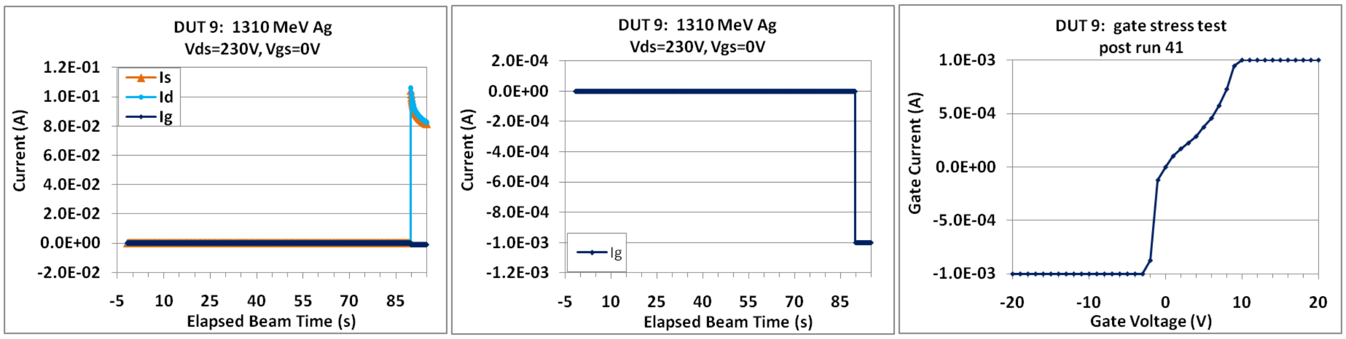

Figure C3. Gate, drain, and source currents during irradiation (middle plot shows gate current at higher resolution), and gate current during post-run gate stress test. The sudden high source and drain currents occurred in the same capture time window as the jump in gate current; gate power supply was limited to 1mA.

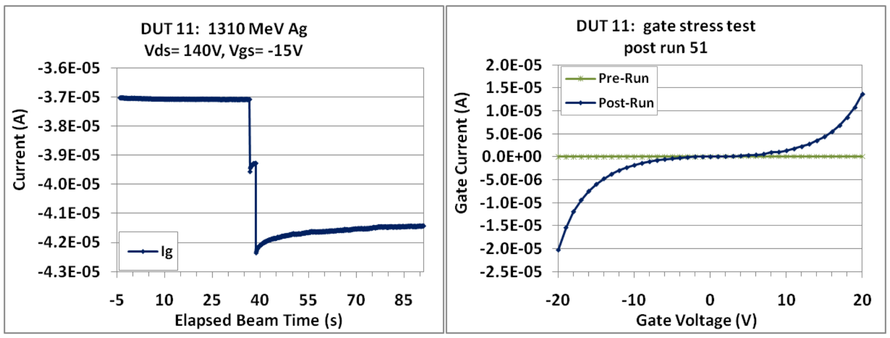

Figure C4A. Gate current during irradiation (left) and during gate stress test (right). Note the step in the gate current during irradiation suggesting two microbreaks from two different ion strikes. The initial current level